EFFECT OF FRACTIONATED FLY ASH AND SILICA FUME ON HIGH STRENGTH CONCRETE

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ABSTRACT

Fly ash is fractionated into different small ranges of particle size distribution. The very fine particle size of fractionated fly ash (smaller than 5 microns) was employed to produce high strength fly ash concrete. Fifteen and twenty five percent of fly ash by weight of cementitious materials were used in the concrete mix as cement replacement. Silica fume in the powder form was also added with the same proportion as fly ash. The compressive strength of fly ash and silica fume concrete was determined and compared to the control high strength concrete. The results show that the compressive strength of fly ash and silica fume concrete achieves a strength of 6000 psi (42 MPa) after 7 days of curing. The rate of strength gain of concrete made from silica fume is very fast at early age but seems to slow down after 7 days. Its strength is almost the same as the control strength at 28 days. High strength concrete made from fractionated fly ash behaves differently that at the early age, the strength of fly ash concrete is lower than those of control and of silica fume concrete. After 14 days, the use of fractionated fly ash in concrete produces the same strength as the control concrete. While at 28 days, the strengths of fly ash concrete are higher than both the control and silica fume concrete. The strengths of these fly ash concretes are in the order of about 8500 psi (58 MPa) whereas the strength for the control and silica fume concretes are about 8000 psi (55 MPa). The compressive strengths of fly ash concrete are in the range of 107% to 115% of the control concrete at the age of 90 days. The results obtained here suggest that fractionated fly ash is a suitable material to produce high strength concrete. The use of fly ash in concrete not only eliminates the cost incurred for the disposal of fly ash but also reduces the cost of high strength concrete.

INTRODUCTION

ACI committee 363 has specified high strength concrete as concrete with a compressive strength of 6000 psi (41 MPa) or greater (ACI 363, 1990). The basic concept to produce high strength concrete is to lower the water/cement ratio as much as possible, usually in the range of 0.25 to 0.30. In achieving this w/c ratio, many high strength concretes incorporate chemical admixtures, such as water reducing agents or high-range water reducing agents or superplasticizers and mineral admixtures such as fly ash or silica fume. The use of a good quality fly ash, meeting specification of ASTM C-618 Class F, is a must in the production of high strength concrete (Task Force Report No. 5, 1977). The fly ash added serves two purposes, one as pozzolanic material to provide additional C-S-H, and the other as filler to reduce voids between cement particles. Optimum amounts are in the range of 10% to 15% by weight of the cement. This may vary considerably in different areas due to the physical and chemical properties of the pozzolan and its reaction with various cements. When silica fume and fly ash were used, the optimum mix is a combination of 10% silica fume with 15% fly ash or slag by volume (Mehta and Aitcin 1990). Silica in the combined mixture provides early strength to concrete while fly ash which is an inert material serves as retarder but provides long term strength. Most high strength concrete mixes presently used contained both silica fume and fly ash.

The use of fly ash in high strength concrete undoubtedly has been demonstrated to be beneficial to the integrity of the composites as well as the economical aspect of the final products. In any event, it should be noted that in such an application, fly ash was often used as generic material. While global performance of high strength fly ash concrete is satisfactory, a clear understanding of how fly ash actually performs in high strength concrete environment remains unknown. This is primarily due to the lack of understanding on the behavior of the fly ash used. The present study uses series of fly ash of known origin, formation, physical and chemical characteristics. With these information, the authors intend to study the role of fly ash in high strength concrete. Of particular interest will be the key parameters of fly ash governing the strength development of the final cement composites.

In this research, testing is made to evaluate the effect of silica fume and fly ash when used as a cement based matrix in concrete. Silica fume in the powder form and the finest fly ash from the dry and wet bottom ashes (3F and 13F) are mixed with concrete as 15% and 25% cement replacements. Superplasticizer is added to lower the water content in the mix. With a high portion of silica fume in the mix, the superplasticizer is used at 10 ml per pound of the cementitious (cement + fly ash or silica fume) materials.

MATERIALS AND TEST PROGRAM

Materials used in this study consist of standard portland cement type I, siliceous sand (river sand) passing sieve No. 4, coarse aggregate with a maximum size of 3/8 inch, fly ash, silica fume, superplasticizer, and water. Two different kinds of fly ash from the utilities in New Jersey were selected for this study. Fly ash of class 13F was obtained from boiler burning coal at a temperature higher than the fusion point of fly ash while class 3F fly ash the temperature in the boiler was lower than the ash fusion temperature. These fly ashes were obtained by separated the original feed fly ash (fly ash received from the utility silo). 3F and 13F fly ashes were very fine with maximum particle size of less than 5 microns and were used to produce high strength fly ash concrete. Since the particle sizes of fly ash are very fine, they contribute strength to the concrete faster than using the original fly ash that comes directly from the utility. Fifteen and twenty five percent of fly ash by weight of cementitious materials were used in the concrete as cement replacement. Silica fume was also used with the same proportion as fly ash. The compressive strength of high strength fly ash concrete and silica fume concrete were determined and compared. The mix proportions of high strength fly ash and silica fume concrete are shown in Table 1.

Table 1 Mix Proportion of High Strength Fly Ash and Silica Fume Concrete

Ingredient	CSF, Control (lb)	15% Repl. (lb)	25% Repl (lb)
Cement	10	8.5	7.5
Fly Ash or Silica Fume	--	1.5	2.5
River Sand	20	20	20
Aggregate, Basalt 3/8"	30	30	30
Superplasticizer	100 ml	100 ml	100 ml
Water	4.17	4.17	4.17
Water/(Cementitious)	0.417	0.417	0.417

RESULTS AND DISCUSSIONS

Chemical Composition of Fly Ash and Cement

Table 2 shows the chemical composition of fly ash, and cement used in this study. According to ASTM C-618 (1990), both fly ashes (3F and 13F) are classified as Class F fly ash since the oxide of $SiO_2 + Al_2O_3 + Fe_2O_3$ are higher than 70%. It should also be noted that cement is rich with CaO while the two fly ashes used have only about 3 and 6%. On the other hand, the silica content in cement is only 20% while both ashes have about 40 and 50% of silica content. The loss on ignition (LOI) which is a measure of the carbon content indicates that fly ash consists of about 3-5% of LOI while cement has only 0.73%. Other key variations between cement and fly ash are the alumina and ferrous oxide contents.

Table 2 Chemical Composition of Fractionated Fly Ash and Cement

	Chemical Composition (%)								
Sam	LOI	SO_3	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	MgO	Na_2O
CEM	0.73	2.53	20.07	8.84	1.41	60.14	0.86	2.49'	0.28
3F	4.97	1.69	49.89	26.94	5.43	2.99	1.76	0.99	0.33
13F	2.67	3.81	38.93	24.91	12.89	6.85	2.10	1.55	1.31

Particle Size Analysis of Fly Ash

The particle size distributions of fractionated fly ashes are shown in Fig. 1. In case of the 3F fly ash, the finest of dry bottom fly ash, 3F (90%-5 um) means that 90% of the fly ash particles are smaller than 5 microns. The mean diameters of 3F and 13F are 2.11 and 1.84 microns, respectively. When the particle sizes are smaller, they have more spherical particles in the fraction (Hemming and Berry 1986), resulting in the reduction of the water requirement to produce the same workability.

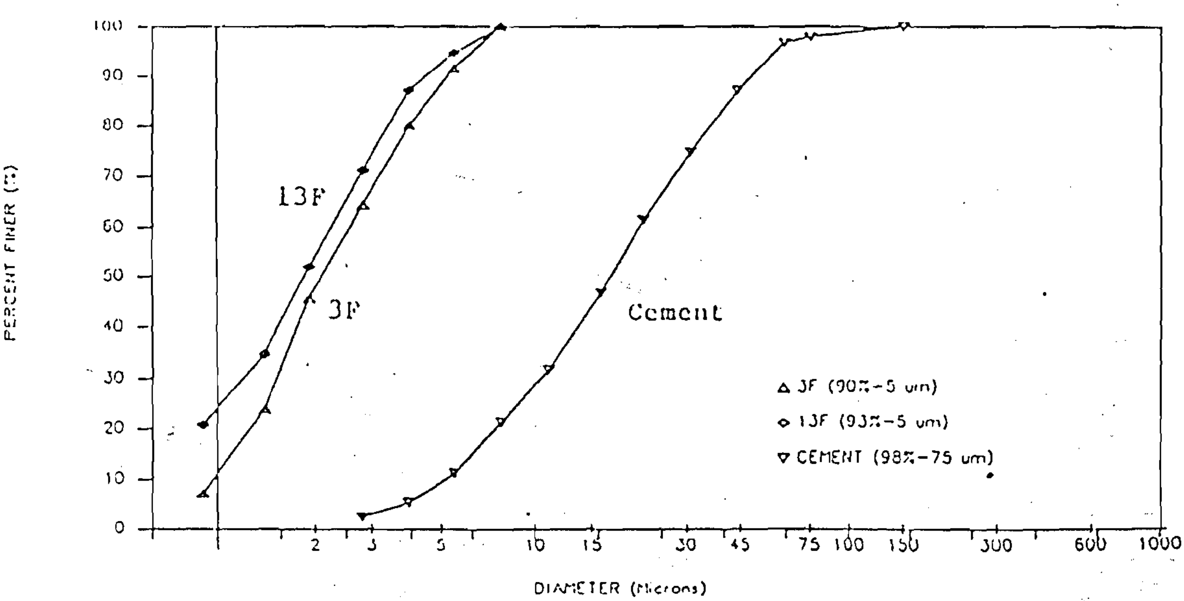

Fig.1 Particle Size Distributions of Fractionated Fly Ash and Cement

Fineness of Fractionated Fly Ash

The fineness of fly ashes both by wet sieve analysis and by the Blaine fineness together with the specific gravity of fly ashes are shown in Table 3. Mean diameter, the diameter of which 50 percent of particles are larger than this size, is also presented in this Table. It should be noted that by using the sieve No. 325 method, the fractionated fly ash samples 3F and 13F have the same fineness since all of them have zero value retained on this sieve.

Table 3 Fineness of Cement and Fractionated Fly Ashes

Sam. No.	Specific Gravity (g/cm^3)	Fineness Retained 45 um (%)	Fineness Blaine (cm^2/g)	Mean Diameter (um)
CEM	3.12	-	3815	-
3F	2.54	0	7844	2.11
13F	2.75	0	11241	1.84

Compressive Strength of High Strength Fly Ash and Silica Fume Concrete

Sample CSF represents the control sample, without any fly ash or silica fume. Samples CSF15 and CSF25 are concretes with 15% and 25% of the weight of cementitious materials replaced by silica fume while samples C3F15 and C3F25 are concretes with 15% and 25% replaced by 3F fly ash. And, samples C13F15 and C13F25 are concretes with 15% and 25% of cement replaced by the 13F fly ash. Table 4 shows the compressive strength of high strength fly ash and silica fume concrete. Table 5 is the percentage compressive strength of high strength fly ash and silica fume concrete compared with the control CSF sample. Figs. 2 and 3 are the relationship between the compressive strength of high strength concrete and age when using 15% and 25% replacement of cement by fly ash or silica fume in the mix.

Table 4 Compressive Strength of High Strength Fly Ash and Silica Fume Concrete

Sample No.	Compressive Strength (psi) 1-day	7-day	14-day	28-day	56-day	90-day	Slump (cm)
CSF	1912	6352	7346	7881	8645	9322	23
CSF15	2335	7176	7768	8009	8715	9286	1
CSF25	2675	6664	7479	8032	8500	9122	0
C3F15	1216	5855	7056	7820	9031	10023	21
C3F25	1212	5968	7248	8648	9775	10521	20
C13F15	1945	6787	7805	8740	9853	10487	16
C13F25	1782	6091	7240	8561	9814	10748	12

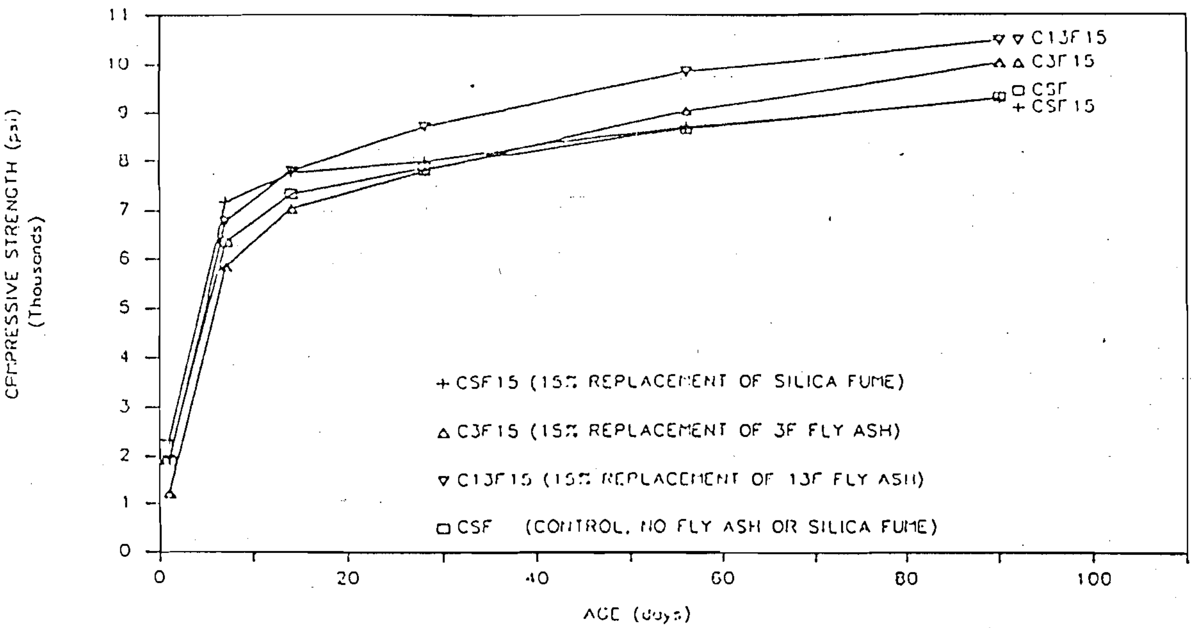

Fig. 2 Relationship between Compressive Strength of High Strength Concrete and Age with 15% Replacement of Fly Ash or Silica Fume

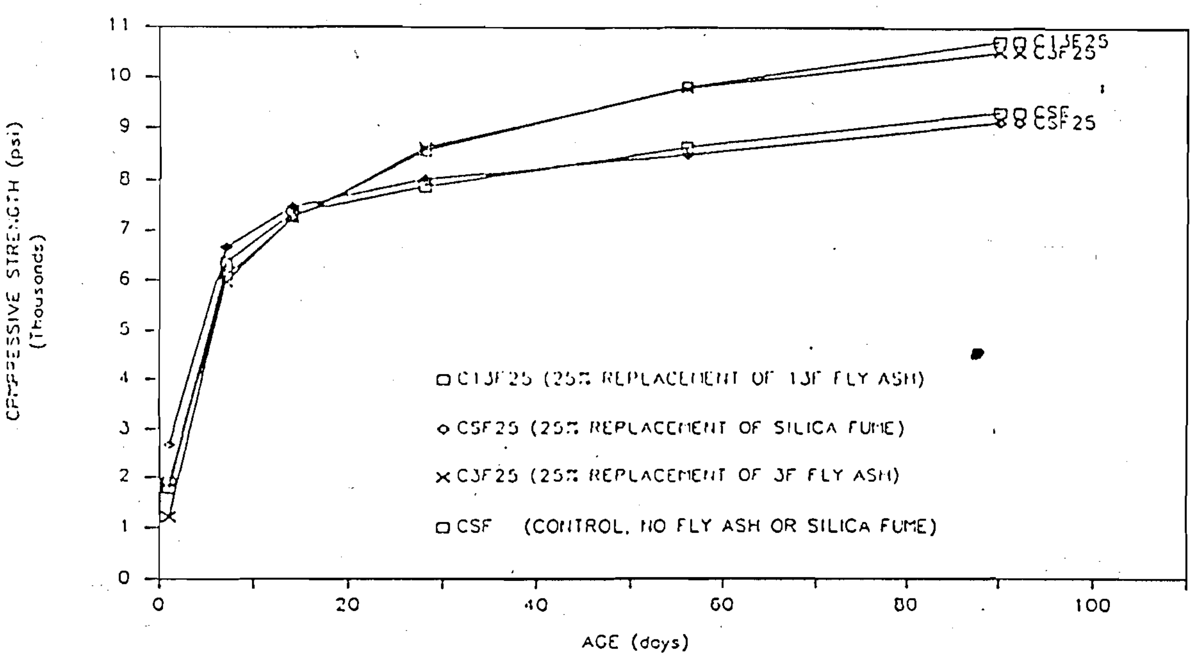

Fig. 3 Relationship between Compressive Strength of High Strength Concrete and Age with 25% Replacement of Fly Ash or Silica Fume

Since the proportions of cementitious materials, sand, coarse aggregate, water, and superplasticizer are constant, the consistency of the fresh concrete depends on the characteristics of cementitious materials. Fresh concrete with 25%

of cement replaced by silica fume had zero slump while the control concrete (CSF) had a 23 cm slump (see Table 4). Because silica fume is a very fine particle material, it has more surface area than cement on an equal weight basis. In general, when the mix proportion of concrete is constant, the mix with silica fume (in powder form) needs more water to maintain the same slump or workability. The slump of concrete with fly ash as cement replacement is lower than that of the control sample. Usually, fly ash of the generic type or original will increase the slump of concrete but, this behavior does not apply to this type of fly ash. 3F and 13F are very fine particle fly ashes, their surface areas as measured by the Blaine method are much higher than that of the cement. The results of this test confirms that very fine particle fly ash will reduce the workability of fresh concrete.

The compressive strength of the control concrete (CSF) varies from 1912 psi (13 MPa) at 1 day to 9322 psi (64 MPa) at 180 days. By the age of 7 days, the compressive strength of CSF reaches 6352 psi (44 MPa), which can be considered as high strength concrete (ACI 363, 1990). The compressive strengths at 1 day of CSF15 and CSF25 are 2335 psi (16 MPa) and 2675 psi (18 MPa), respectively or 22% and 40%, stronger than the control concrete. Concrete with silica fume gains strength very fast at early age. This behavior can be attributed to both the packing and pozzolanic effects. Because particle sizes of silica fume are very small, they fill the voids of the concrete matrix, making concrete denser and more compact after casting. During the curing period, the pozzolanic reaction of silica fume takes place at a faster rate than the fly ash because of its fineness. After 28 days, the strength gain of silica fume concrete slows down and the strength falls below that of the control. The percentage of control strength of high strength silica fume concrete with 25% cement replacement reduces from 140% at 1 day to 98% at 180 days.

High strength concrete made from fly ash behaves in different way. The early strengths of high strength fly ash concrete are usually lower than the control concrete. With 15% cement replacement by the 3F fly ash, the compressive strength of fly ash concrete varies from 1216 psi (8 MPa) at 1 day to 10023 psi (69 MPa) at 180 days or 63% to 108% of the control strength. With 15% replacement of 3F fly ash, the compressive strength at 1 day is expected to be on the order of 80% of the control strength. The lower value observed here may be due to the high dosage of superplasticizer used in this mix. The superplasticizer used in this experiment is about 3 times higher than those recommended by the manufacturer for normal concrete. High dosage of this admixture will generally retard the setting of cement which results in the lower compressive strength at early age. The effect is not as for pronounced in the case of wet bottom fly ash, 13F fly ash. After 7 days, the rate of strength gain of high strength fly ash concrete returns to what would normally be expected. The compressive strength of fly ash concrete is considered to be high strength after 7 days since it exceeds 6000 psi (41 MPa). The strength variation of high strength fly ash concrete with 25% replacement of 13F fly ash varies from 1782 psi (12 MPa) at 1 day to 10748 psi (74 MPa) at 180 days. The greater use of fly ash gives lower compressive strength at the early ages up to 14 days. After 90 days, concrete with higher fly ash content produces higher strength than the concrete with a lower fly ash content. In general, the strength of fly ash concrete using 13F fly ash is higher than those using the 3F fly ash.

Before 7 days, the highest strength found is in the samples with silica fume in the mix. After 14 days, sample CSF15 and C13F15 almost have the same strength of about 7800 psi (54 MPa). At 28 days of curing, high strength concretes using fly ash as cement replacement produced a stronger concrete than for either the control or the silica fume concrete. The strength of samples C13F15, C13F25, and C3F25 are

8740 psi (60 MPa), 8561 psi (59 MPa), and 8648 psi (60 MPa), respectively or 111%, 109%, and 110% as compared with the control strength. As the age increases, the strengths of fly ash concrete also increase. At 90 days, the compressive strengths of fly ash concrete are 107% to 115% of the control concrete.

It is interesting to note that the compressive strength of concrete made with silica fume (both 15% and 25% replacement) have almost the same strength as the control concrete at the age of 90 days. These strengths are in the range of about 9000 psi (62 MPa). It is obvious that silica fume in concrete reacts faster than fly ash and control concrete but the rate becomes slower after 7 days. Figs. 2 and 3 confirm the behavior of high strength silica fume concrete.

CONCLUSIONS

1. Concrete with silica fume has a faster rate of strength gain at early ages than fly ash and control concrete. This behavior can be attributed to the packing and pozzolanic effects. Since the particle sizes of silica fume are very fine, they fill the voids in the fresh concrete and make concrete denser.
2. The early strengths of high strength fly ash concrete are lower than the control and silica fume concrete. But after 28 days of curing, strengths of fly ash concrete are generally higher than those of control high strength concrete.
3. It is obvious that silica fume in concrete reacts faster than fly ash and control concrete but the rate of strength gain becomes slower after 7 days.
4 Fractionated fly ash is a suitable material to produce high strength concrete. The use of fractionated fly ash will lower the cost of concrete.

REFERENCES

ACI Committee 363, 1990, "State-of-the-Art Report on High-Strength Concrete," ACI 363R-84, *ACI Manual of Concrete Practice Part I*, American Concrete Institute, Detroit, 47 pp.

ASTM C 204, 1990, "Test Method for Fineness of Portland Cement by Air Permeability Apparatus," ASTM C 204-89, *Annual Book of ASTM Standards*, Vol. 04.01.

ASTM C 430, 1990, "Test Method for Fineness of Hydraulic Cement by the 45-Micron (No. 325) Sieve," ASTM C 430-89, *Annual Book of ASTM Standards*, Vol. 04.01.

ASTM C 618, 1990, "Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement concrete," ASTM C 618-89a, *Annual Book of ASTM Standards*, Vol. 04.02.

ASTM D 4326, 1990, "Test Method for Major and Minor Elements in Coal and Coke Ash by X-Ray Fluorescence," ASTM D 4326-84, *Annual Book of ASTM Standards*, Vol. 05.05.

Hemming, R.T. and Berry, E.E., 1986, "Speciation in Size and Density Fractionted Fly Ash," *Symposium Proceedings, Fly Ash and Coal Conversion By-Products: Characterization, Utilization and Disposal II*, Material Research Society, Vol. 65, pp. 91-103.

Mehta, P.K. and Aitcin, P.C., 1990, "Principles Underlying Proportion of High-Performance Concrete," *Cement, Concrete, and Aggregates*, Vol. 12, No. 2, pp. 70-78.

Task Force Report No. 5, 1977, "High Strength Concrete in Chicago High-Rise Building," Chicago Committee on High-Rise Building, 66 pp.